The Impact of Nuclear Reaction Rate Uncertainties on Evolutionary Studies of the Nova Outburst

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Abstract. The observable consequences of a nova outburst depend sensitively on the details of the thermonuclear runaway which initiates the outburst. One of the more important sources of uncertainty is the nuclear reaction data used as input for the evolutionary calculations. A recent paper by Starrfield, Truran, Wiescher, & Sparks [1] has demonstrated that changes in the reaction rate library used within a nova simulation have significant effects, not just on the production of individual isotopes (which can change by an order of magnitude), but on global observables such as the peak luminosity and the amount of mass ejected. We will present preliminary results of systematic analyses of the impact of reaction rate uncertainties on nova nucleosynthesis.

I NUCLEAR UNCERTAINTIES IN NOVAE

Observations of nova outbursts have revealed an elemental composition that differs markedly from solar. Theoretical studies indicate that these differences are caused by the combination of convection with explosive hydrogen burning which results in a unique nucleosynthesis that is rich in odd-numbered nuclei such as ^{15}N, ^{17}O and ^{13}C. These nuclei are difficult to form in other astrophysical events. Many of the proton-rich nuclei produced in nova outbursts are radioactive, offering the possibility of direct observation with γ-ray instruments. Potentially important γ-ray producers include ^{26}Al, ^{22}Na, ^{7}Be and ^{18}F.

1) Research at the Oak Ridge National Laboratory is supported by the U.S. Department of Energy under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp.

The observable consequences of a nova outburst depend sensitively on the details of the thermonuclear runaway which initiates the outburst. One of the more important sources of uncertainty is the nuclear reaction data used as input for the evolutionary calculations [1]. A number of features conspire to magnify the effects of nuclear uncertainties on nova nucleosynthesis. Many reactions of relevance to novae involve unstable proton-rich nuclei, making experimental rate determinations difficult. For hydrodynamic conditions typical of novae, many rates depend critically on the properties of a few individual resonances, resulting in wide variation between different rate determinations. Statistical model (Hauser-Feshbach) calculations, which are employed with great success for a large number of reactions [2], are unreliable for rates dominated by individual resonances. The similarity of the nuclear burning and convective timescales results in nuclear burning in novae which is far from the steady state which typifies quiescent burning.

II MONTE CARLO ESTIMATES OF UNCERTAINTIES

Though analysis of the impact of variations in the rates of a few individual reactions has recently been performed using one-dimension hydrodynamic models [3], analysis of the impact of the complete set of possible reaction rate variations in such hydrodynamic models remains computationally prohibitive. We therefore begin by examining in detail the nucleosynthesis of individual zones, using hydrodynamic trajectories (temperature and density as a function of time) drawn from nova outburst models. Such one zone, post-processing nucleosynthesis simulations are a common means of estimating nova nucleosynthesis (see e.g., [4,5]). For this presentation we are using a hydrodynamic trajectory for an inner zone of a $1.35 M_{\odot}$ ONeMg WD which is similar to that described in [6]. These calculations were performed using a nuclear network with 87 species, composed of elements from n and H to S, including all isotopes between the proton drip line and the most massive stable isotope.

Figure 1 shows the abundances of each species at the end of the simulation, 5.2×10^{5} sec after peak temperature. Because of the long time which has elapsed, the unstable proton-rich nuclei have decayed, reducing their abundances to less than 10^{-20}. To investigate the extent to which nuclear reaction uncertainties translate into abundance differences, we use a Monte Carlo technique which assigns to each reaction rate in the nuclear network a random enhancement factor. The error bars displayed in Fig. 1 are the 90% confidence intervals which result from 992 Monte Carlo iterations. Monte Carlo methods have been employed with great success in the analysis of Big Bang nucleosynthesis [7], but have not previously been applied to other thermonuclear burning environments.

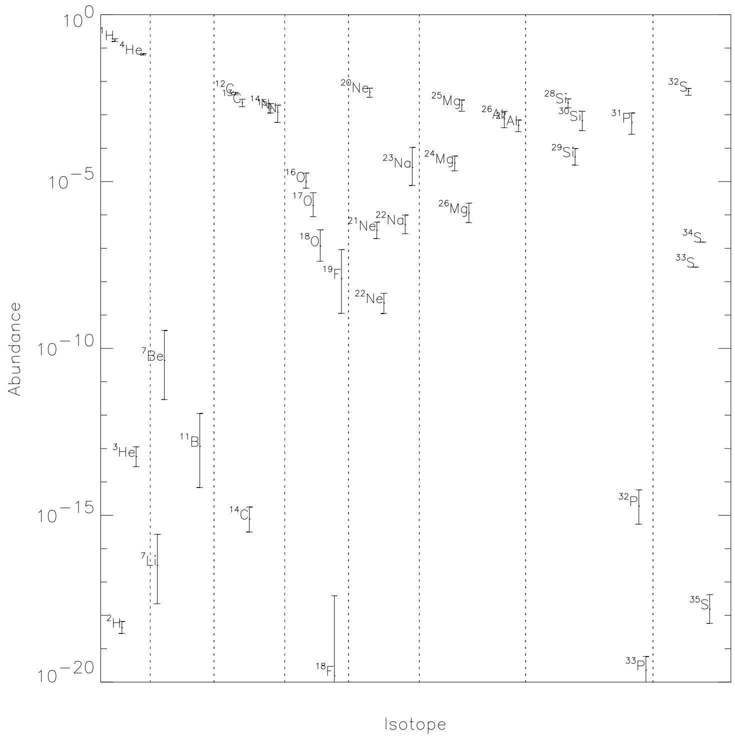

FIGURE 1. Final Abundances (elapsed time = 5.2×10^5 sec after peak).

The reaction rate enhancement factors are distributed according to the log-normal distribution, which is the correct uncertainty distribution for quantities like reaction rates which are manifestly positive [8],

$$p_{log-normal}(x) = \frac{1}{\sqrt{2}\,\pi\beta x} \exp\left(-\frac{(\ln x - \alpha)^2}{2\beta^2}\right) , \tag{1}$$

where α and β are the (logarithmic) mean and standard deviation. For small uncertainties ($< 20\%$), the difference between the log-normal distribution and the normal (Gaussian) distribution is small. However, for uncertainties of larger sizes such as those encountered in this problem, the difference is important. For this preliminary analysis, we have chosen to assign uncertainties of $\sim 50\%$ ($\beta = \ln(1.5)$) both to rates calculated by Hauser-Feshbach methods and also to rates whose measurement require radioactive ion beams. For all other rates we assign $\beta = \ln(1.2)$. Figure 2 plots the resulting abundance distributions for two representative nuclei. Fig. 2 also demonstrates the differences between normal and log-normal distributions for widths of these sizes. These are very conservative uncertainties; relatively few reactions, especially among unstable nuclei, have measurement uncertainties this small.

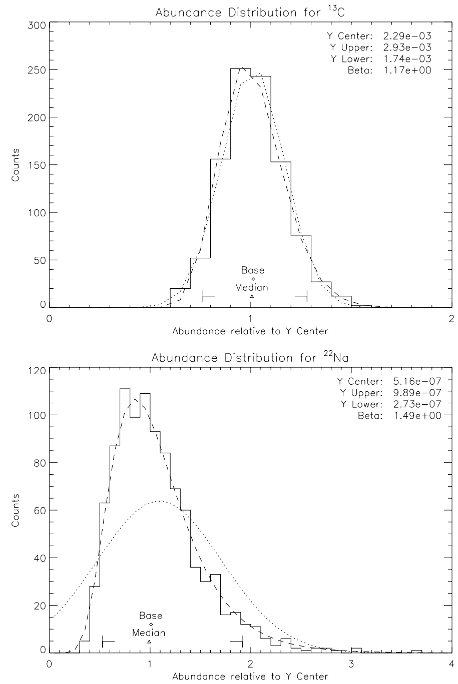

FIGURE 2. The histograms showing deviations in abundance from the mean. The dotted curves are normal distributions with the same (arithmetic) mean and standard deviation as the Monte Carlo distribution. The dashed curves are log-normal distributions with (logarithmic) mean and standard deviation from the Monte Carlo. Y Center, Y Upper, and Y Lower correspond, respectively, to the central abundance and the upper and lower error bars from Fig. 1.

III RESULTS

As evidenced by the error bars in Fig. 1, the impact of even our conservatively chosen variations in reaction rates on the nucleosynthesis is large. While broader conclusions will require analysis of additional hydrodynamic trajectories, a number of interesting points can be made from the analysis of this single trajectory. The impact on the rate of energy production is small. At the 90% confidence level, variations in the amount of hydrogen consumed represent $\sim 10\%$ variation in the thermonuclear energy released. For the most abundant metals (those which represent more than 1% of the mass), 2σ variations by factors of 1.1 to 1.4 are common, with some of these nuclei showing 2σ variations as large as a factor of 2, for example, ^{15}N ($2.1\times$) and ^{30}Si ($2.3\times$). For the γ-ray source nuclei ^{22}Na and ^{26}Al, the 90% confidence interval includes variations of nearly a factor of 2, representing almost a factor of 4 difference in the distance from which novae may be observed by γ-ray telescopes. For ^{7}Be, the 90% confidence interval spans more than 2 orders of magnitude.

Such large uncertainties in the nucleosynthesis, resulting from poorly known nuclear reaction rates, constrain our ability to make detailed comparisons between theoretical models for the nova outburst and astrophysical observations to a degree which is often ignored. Improved knowledge of these uncertain rates, both experimental and theoretical, is necessary to provide tight constraints on the nova outburst from its nucleosynthetic products.

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